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PROJECT APOLLO

CSM FUEL REQUIREMENTS FOR A LM RESCUE IN LUNAR ORBIT

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SUMMARY

A manned hybrid simulation has been conducted to determine the Service Module (SM) RCS fuel requirements for a Lunar Module (LM) rescue in lunar orbit. The objective of this study is to define more fully the CSM consumables requirements, and the effect of a VHF ranging device, in the event that the LM becomes unable to complete the concentric rendezvous sequence following powered ascent from the lunar surface.

This study investigated only the terminal phase of rendezvous starting at TPI. Thus, the study assumed that the LM had completed the powered ascent, from a 45°E landing site, and insertion into a 10 x 30 nautical mile orbit. It was also assumed the CSI and CDH maneuvers had been made.

All primary mode navigation, guidance, and control tasks were completed by the CSM using the sextant (SXT) only, or the SXT and VHF, for improvement of MSFN derived state vectors. In the backup (PNGCS failed) mode the ground furnished concentric sequence maneuvers to the CSM, while the TPI and midcourse maneuvers were determined using a line-of-sight rate correction technique developed by the GCD. When VHF ranging information was available in the backup mode, Gemini backup charts were used to determine the maneuvers. The resulting SM-RCS fuel requirements were 418 and 495 pounds for the primary and backup modes, respectively. The addition of a VHF ranging device saves an average of 18 and 52 pounds of SM-RCS fuel in the primary and backup modes, respectively.

INTRODUCTION

A piloted simulation study of the LM rescue in Lunar Orbit has been conducted by GCD to aid in the planning of the Lunar Landing Mission and to determine the adequacy of the SM-RCS fuel budget. Also included in the study was an evaluation of the usefulness of state vector improvement using VHF ranging data for the CSM and its effect on SM-RCS fuel requirements for both primary and backup mode rendezvous. It is the purpose of this report to present and discuss the results obtained.

SIMULATION DESCRIPTION

The motion of the CSM was simulated in six degrees-of-freedom and that of the LM in three degrees-of-freedom using general purpose computers. The long period dynamics (orbital mechanics) were programmed on a digital differential analyzer (DDA) and the short period dynamics (rotational motion) on analog computers. The CM-SCS was used for attitude control and was simulated in a simplified Block II configuration. The jet select logic was simplified. A simulator cockpit was coupled with the general purpose computers for pilot monitoring and control of the rendezvous trajectory. A virtual image display system, driven by the DDA, displayed a model of the LM/SIVB to the pilot in simulated three dimensional space. For a detailed description of the simulation mechanization, refer to Reference

SIMULATED RENDEZVOUS TRAJECTORIES

The CSM rendezvous situation simulated was one in which the LM becomes inactive immediately after insertion from a 45° East landing site, thus leaving the LM in an elliptical (10 n mi x 30 n mi) orbit. The simulation used for this study, however, was programmed only for circular target orbits. Therefore, it was decided to simulate the LM in a 10 n mi circular orbit rather than the elliptical one discussed above.

The trajectory dispersions caused by navigation errors on both vehicles were combined and applied only to the CSM trajectory. In other words, the LM was placed in an exact 20 n mi circular orbit and the CSM relative trajectory was dispersed to account for navigation errors on both vehicles. Table I gives the LM inertial state vectors and CSM relative inertial state vectors (designated actual trajectory) used for each navigation case.

ONBOARD STATE VECTOR ERRORS

State vector errors based on the navigation available in each case were obtained from an off-line digital simulation and added to the CSM actual relative trajectory to determine the CSM onboard relative trajectory. These initial onboard state vectors are given in Table I and represent navigation both with and without VHF ranging information to aid in state vector improvement.

SIMULATED CREW PROCEDURES

In cases where the PNGCS was assumed to be working, the midcourse correction was computed onboard and applied at TPI + 27:00 minutes. These runs are initiated at TPI + 26:00 minutes. In primary mode, the pilot used the range and range-rate data displayed on the DSKY to monitor the progress of the rendezvous and to control the braking phase. In backup mode where VHF range data was present, range-rate was derived mentally every few minutes by differencing range over a one minute time interval. In the backup mode where no direct range data was available, both range and range-rate were estimated using elapsed time, backup charts, and visual cues. The procedures are summarized in Table II.

SIMULATION RESULTS

The SM-RCS data obtained in each simulation run is listed in Table III in terms of roll (Wp), pitch (Wq), and yaw (Wr) attitude control fuel and translation ΔV along the three body axes ($\Delta V_X, \Delta V_Y, \Delta V_Z$). The translation ΔV is also given in terms of TPI, MCC's, and TPF maneuvers. It should be noted, however, that the TPI attitude and translation fuel is not included in the fuel numbers listed by axes (Wp, Wq, Wr, $\Delta V_X, \Delta V_Y, \Delta V_Z$) for the runs where the PGNCS was operational since these runs started after TPI. The TPI attitude and translation fuel is included in TOTAL FUEL for these runs. In cases where the PGNCS was operational, the SCS attitude fuel obtained in the simulation was reduced by $\frac{2 \int_Z (\Delta V_X)}{1}$ (where $\int z$ = cg offset in Z direction and 1 = thruster moment arm) for pitch (Wq) and $\frac{2 \int_Y (\Delta V_X)}{1}$ (where $\int_y$ = c.g. offset in Y direction) for yaw (Wr) to reflect equivalent DAP operation with X-axis thruster priority logic. A conversion of 4.3 lb/fps was used to obtain total fuel.

DISCUSSION OF RESULTS

It can be seen from the SM-RCS Fuel Required given in Table IV that an average saving of 18 and 52 pounds of SM-RCS fuel was realized in the primary and backup modes repsectively when VHF range information was available for navigation. The bulk of this saving occurred in the midcourse correction phase because of a lower trajectory dispersion and a more accurate calculation of the MCC when VHF range information was available.

Although a substantial saving in fuel was not realized in the braking phase using VHF range, it did make the monitor and control tasks much simpler which resulted in a more standard approach trajectory to the target. It is significant to note that the fuel required in the braking phase for both range rate and LOS rate control averaged very near 50 fps for both primary and backup modes, with and without VHF ranging.

CONCLUSIONS

Based on the results of this study, the conclusions are:

1. A CSM resuce of the LM in lunar orbit will require an average of 418 pounds of SM-RCS fuel in the primary mode and 495 pounds in the backup mode for the phase starting just prior to TPI and ending at

the docking interface ($\dot{R} \leq 1$ fps; LOS Rate ≤ 0.1 mr/sec). This assumes initialization errors as defined in Table I.

2. The addition of a VHF ranging device will save an average of 18 and 52 pounds of SM-RCS fuel in the primary and backup modes respectively, for this phase.

3. The addition of a VHF ranging device will make the terminal phase much easier to fly, thus providing for a more standard approach path to the target.

REFERENCES

Simpson, Ronald W. and Smith, Herbert E., Jr.: Apollo Rendezvous with Command Module Active. MSC Internal Note No. 67-EG-23, Sept. 28, 1967.

TABLE I

CSM Relative Inertial State Vectors

Case	X_I (FT)	Y_I (FT)	Z_I (FT)	$\dot{X}_I$ (FPS)	$\dot{Y}_I$ (FPS)	$\dot{Z}_I$ (FPS)		
NOMINAL TRAJECTORY STARTING AT TPI + 26 min								
10E - N	+9429.366	-63.611	-26,457.576	-11.239640	-0.036127	+39.907928	Onboard trajectory	
"	+9429.366	-63.611	-26,457.576	-11.239640	-0.036127	+39.907928	Actual trajectory	
SXT ONLY STARTING AT TPI + 26 min								
10E - S	+6497.951	+1319.453	-33,738.458	-14.694492	+0.608949	+40.01389	Onboard trajectory	PLAN
"	+6659.951	+1241.453	-32,373.458	-14.034492	+0.068949	+41.51389	Actual trajectory	I
SXT PLUS VHF STARTING AT TPI + 26 min								
10E - SV	+3902.395	-656.947	-33,323.356	-14.433882	-0.147661	+40.373313	Onboard trajectory	PLAN
"	+3977.395	-902.947	-33,131.356	-14.562881	+0.317339	+40.631313	Actual trajectory	I
MSFN ONLY STARTING AT TPI - 10 min								
10E - M	No onboard trajectory; onboard computer failed						Onboard trajectory	
"	+170,401.900	+2000.000	-53,902.851	-27.218871	+8.000000	+152.149134	Actual trajectory	

LM Inertial State Vectors

Case	X_{LM} (FT)	Y_{LM} (FT)	Z_{LM} (FT)	$\dot{X}_{LM}$ (FPS)	$\dot{Y}_{LM}$ (FPS)	$\dot{Z}_{LM}$ (FPS)
	0 ft	0 ft	-5,823,917.30ft	+5452.13501fps	0fps	0

TABLE II. - CREW PROCEDURES FOR SIMULATION
OF LM RESCUE IN LUNAR ORBIT

Time	Event	Crew
0:00	TPI	Made by MPAD.
26:00	Pre TPM	1. Start simulation run. 2. Place all attitude control mode switches in RATE COMMAND. 3. Maneuver to burn attitude with rate of 0.1°/sec (boresight X-axis).
26:30	Pre TPM	1. Calculate MCC maneuver using onboard routines.
27:00	TPM	1. Manually thrust out MCC using RCS jets along each body axis.
28:00	Pre TPF	1. Place pitch and yaw attitude control switches in MIN IMP. 2. Boresight target in reticle and track to monitor the LOS rate.
30:00	Pre TPF	(Backup Mode MCC) 1. Place all attitude control mode switches in RATE COMMAND. 2. Boresight target in collimated reticle. 3. Time LOS drift from center of reticle out to inner circle of reticle. 4. Read MCC from backup chart using LOS drift elapsed time. 5. Boresight target and manually thrust out MCC using RCS jets along each body axis. 6. Place pitch and yaw attitude control switches in MIN IMP.
34:30	Pre TPF	1. Boresight target and read computed SHAFT/TRUNNION angles (A&E) for estimated LOS. If either angle is greater than 5 degrees, do not use computed range and range rate in braking phase.
35:00	Pre TPF	(Backup Mode MCC) Same as at TPI + 30:00 min.
35:30	Pre TPF	1. Place all attitude control switches in RATE COMMAND. 2. Thrust inplane and out-of-plane LOS Rates to zero using RCS jets. 3. Track target and maintain LOS Rates at zero.
38:30	TPF	1. Brake range rate to -15 fps. (If range rate uncertainty is ± 5 fps or greater, do not brake at this point.) 2. Track target and maintain LOS Rates at zero.
44:00	TPF	Brake range rate to -5 fps.

CSM Rescue of LM in Lunar Orbit

TABLE III

Target Case	ΔH (n mi)	Navigation	Ev(MR) (SSI)	Ev(MR) (CSM)	Ev(FPS) (TPI)	Ev(FPS) (MCC)	Control Procedure	Pilot	Attitude Fuel W_p (lbs)	W_q (lbs)	W_r (lbs)	W_{TOT} (lbs)	Translation Fuel ΔV_x (fps)	ΔV_y (fps)	ΔV_z (fps)	ΔV_{TOT} (fps)	TPI ΔV (R/Ang)	MCC #1 ΔV (R/Ang)	MCC #2 ΔV (R/Ang)	MCC #3 ΔV (R/Ang)	TPF ΔV (R/Ang)	Attitude Fuel TPF Brake (lbs)	Transl Fuel TPF (lbs)	Att/Trans Fuel MC/TPF (lbs)	Total Fuel (lbs)
Nom (1)	10	perfect	0	0	0	0	PGNCS	Leffler	3.74	10.34	3.44	11.52	21.76	0	4.34	26.30	16.00/0	0	0	0	21.74/4.34	4.1	68.80	190.61	209.51
" (2)	"	"	"	"	"	"	"	Vogel	4.56	7.52	2.14	14.22	22.20	0	9.70	31.90	"	"	"	"	22.20/9.70	"	"	151.39	230.29
" (3)	"	"	"	"	"	"	"	Leffler	2.90	13.12	6.00	25.08	52.00	0	5.00	57.00	"	"	"	"	52.00/5.00	"	"	138.12	211.02
" (4)	"	"	"	"	"	"	"	Smith	4.46	11.09	3.24	30.78	20.00	0	10.00	30.00	"	"	"	"	20.00/10.00	"	"	149.78	232.61
10E-3 (5)	10	[illegible]	15.5	4.3	2.7	1.0	PGNCS	Smith	6.64	29.20	3.80	38.15	34.00	5.10	27.42	44.52	18.3/4.1	8.20/11.60	0	0	21.80/25.92	5.8	96.32	39.16	431.20
" (6)	"	"	"	"	"	"	"	Smith	4.33	13.38	.76	[illegible]	34.50	10.40	25.97	73.10	"	8.20/11.60	"	"	22.00/20.97	"	"	336.75	438.77
" (7)	"	"	"	"	"	"	"	Simpson	6.28	21.56	1.80	29.75	23.00	4.08	26.14	73.19	"	3.40/10.90	"	"	22.40/22.19	"	"	[illegible]	436.56
" (15)	"	"	"	"	"	"	"	Smith	6.16	7.02	1.40	15.55	38.70	8.46	19.60	60.76	"	4.50/9.19	"	"	23.20/24.17	"	"	276.65	378.77
" (18)			"	"	"	"	"	Smith	6.44	1.94	1.15	30.53	35.00	7.64	29.16	71.80	"	6.50/9.19	"	"	26.52/22.6	"	"	392.37	494.39
10E-3V (8)	10	[illegible]	13.7	5.4	1.2	0.6	PGNCS	Smith	7.10	21.46	1.48	31.74	23.00	6.96	37.00	67.10	18.00/8.00	*36/6.70	0	0	18.64/22.19	5.8	95.30	320.37	421.37
" (9)	"	"	"	"	"	"	"	Simpson	8.02	16.19	1.44	25.57	[illegible]	[illegible]	[illegible]	76.83	"	* 2.90	"	"	41.78/26.13	"	"	363.36	464.96
" (10)	"	"	"	"	"	"	"	Smith	5.60	18.12	1.62	25.34	[illegible]	[illegible]	[illegible]	78.67	"	3.36/6.70	"	"	30.96/22.3	"	"	336.82	431.42
" (11)	"	"	"	"	"	"	"	Simpson	6.40	16.28	4.64	[illegible]	[illegible]	2.90	[illegible]	[illegible]	"	* 2.90	"	"	22.80/19.13	"	"	294.40	396.00
" (12)	"	"	"	"	"	"	"	Smith	5.08	12.12	1.95	[illegible]	[illegible]	3.25	11.91	[illegible]	"	3.36/6.70	"	"	23.70/8.51	"	"	304.54	395.14
" (13)	"	"	"	"	"	"	"	Smith	7.30	11.00	[illegible]	[illegible]	[illegible]	7.00	20.09	36.8	"	3.36/6.70	"	"	24.44/20.10	"	"	272.35	373.85
10E-11	10	[illegible]	–	–	8 (out-of-plane)	–	Manual Gun Sight	Smith	14.64	29.46	[illegible]	[illegible]	33.26	19.16	19.90	74.92	[illegible]	9/20	3/8	0	[illegible]	–	–	–	398.32
"	"	"	"	"	"	"	"	Smith	16.48	[illegible]	[illegible]	99.98	[illegible]	16.86	37.29	96.63	[illegible]	0/7	4/6	3/6	23.0/24.6	–	–	–	514.57
"	"	"	"	"	"	"	"	Smith	18.40	[illegible]	[illegible]	79.4	48.00	19.10	31.60	78.70	[illegible]	5/0	0	0	24.0/25.7		–	–	459.16
10E-11	10	MSFN	–	–	8 (out-of-plane)	–	Manual 8-ball chart	Simpson	8.00	[illegible]	[illegible]	66.44	46.22	12.80	70.10	89.10	[illegible]	8/10	0/3	0	22.6/28.	–	–	–	480.10
"	"	"	"	"	"	"	"	Simpson	11.60	[illegible]	[illegible]	91.48	61.86	18.12	17.63	97.29	[illegible]	12/9	4/4	0	21.26/23.	–	–	–	511.12
"	"	"	"	"	"	"	"	Simpson	10.94	[illegible]	314.78	102.24	59.88	12.34	26.66	99.10	[illegible]	2/9	9/9	8/8	24.6/16.0	–	–	–	525.41

* MCC#1 - vector summed R + 1.05 correction, used X-body thrusters

TABLE IV

SM-RCS AVERAGE FUEL REQUIRED

Event	Primary Mode		Backup Mode	
	SXT	SXT/VHF	COAS	COAS/VHF
TPI (translation)	96#	96#	69#	85#
TPM (translation)	77#	54#	126#	62#
TPF (translation)	220#	226#	213#	213#
Translation Control Subtotal (TPI, TPM, TPF)	393#	376#	408#	360#
Attitude Control Subtotal (TPI, TPM, TPF)	25#	24#	87#	83#
Total	418#	400#	495#	443#